PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

Modeling Edge Localized Modes

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PPPL/UMD Theory/Stellarator Mini-Meeting

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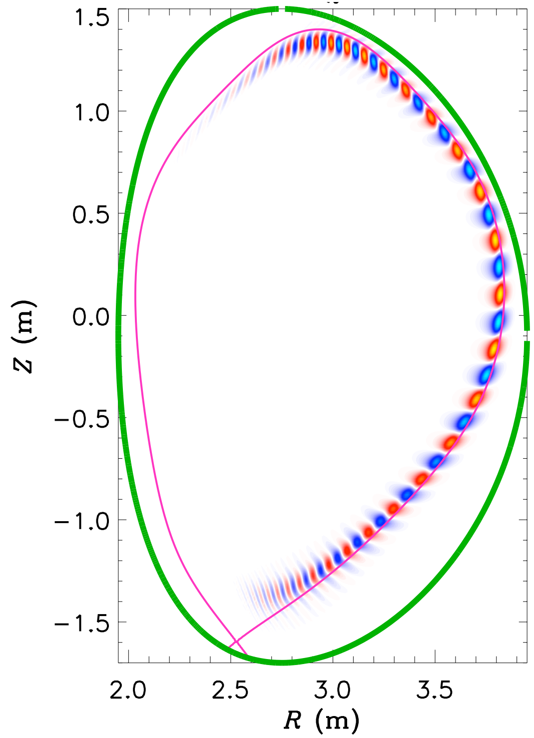
ELMs Represent Major Challenge to Successful Tokamak Reactor

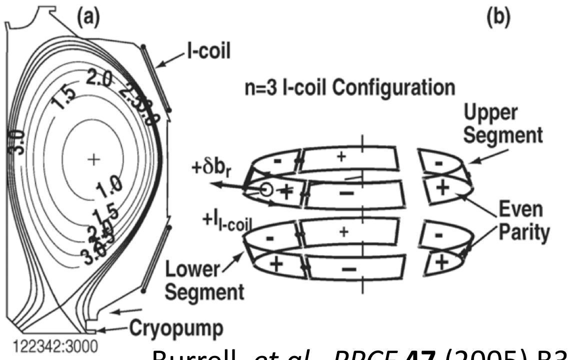
- Edge Localized Modes (ELMs)
  - Intermittent bursts of heat from plasma edge
  - Present in most H-mode scenarios
  - Understood to be ideal-MHD instabilities of the plasma edge (peeling-ballooning modes)
  - Expected to melt / erode divertor in ITER if not mitigated

- "ITER and later reactors will require very large reductions in the magnitude and frequency of both ELMs and major disruptions based on extrapolations from current experiments"
  - http://science.energy.gov/~/media/fes/pdf/program-news/Transients_Report.pdf

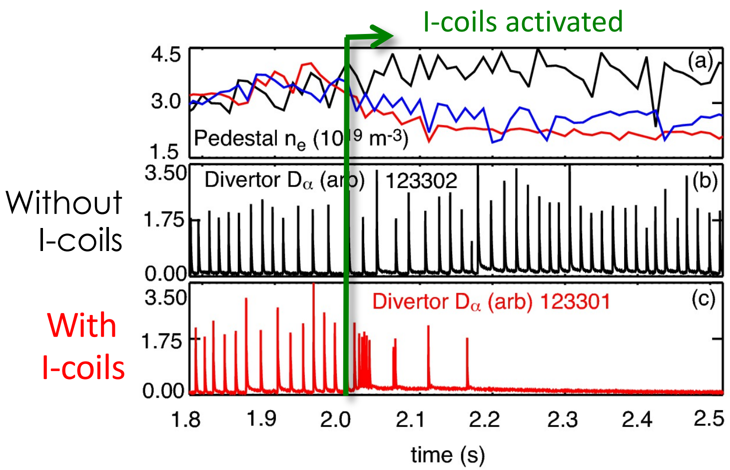


RMPs are a Primary Strategy for ELM Mitigation

- ELMs can be completely suppressed by applying non-axisymmetric Resonant Magnetic Perturbations (RMPs)
- Works on some tokamaks
  - Works on DIII-D, AUG, KSTAR
  - Doesn't work on NSTX, MAST, JET
- Only works for certain conditions
  - q_{95} windows, collisionality/density thresholds
- Only predictive model of ELM suppression is 10 years old and does not consider plasma response: Fenstermacher *et al*, *Phys. Plasmas* **15**, 056122 (2008)
  - We know this is not very accurate!
- **We can't predict when RMP ELM suppression will work**
  - **This presents big risks for ITER!**



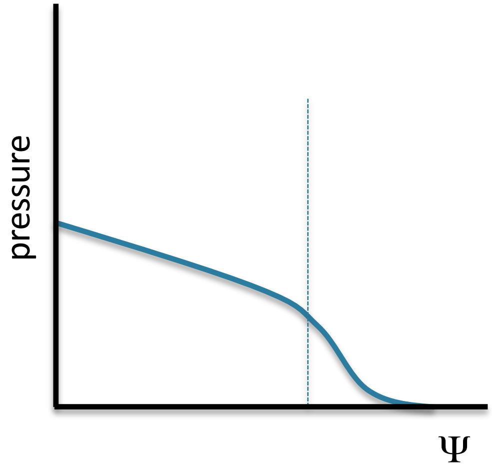
Burrell, *et al.* *PPCF* **47** (2005) B37



Evans, *et al.* *Phys. Plasmas* **13** (2006)

EPED Model Suggests Suppression Is Due to Enhanced Transport at Pedestal Top

- EPED Model of pedestal structure:
  - Gradient determined by local KBM stability
  - Width grows until global P-B stability threshold is reached (ELM)



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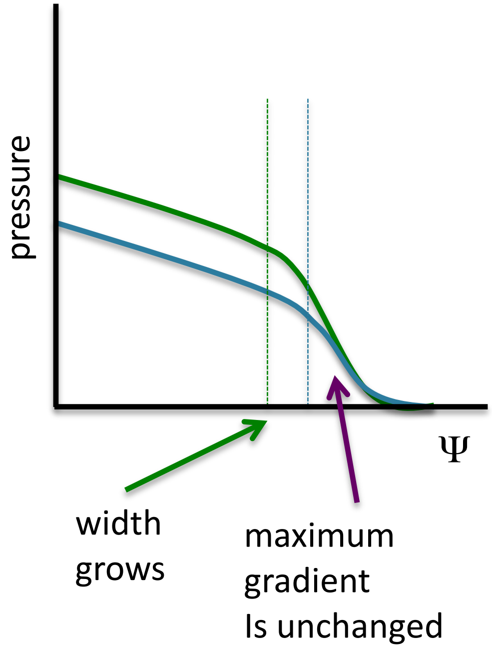

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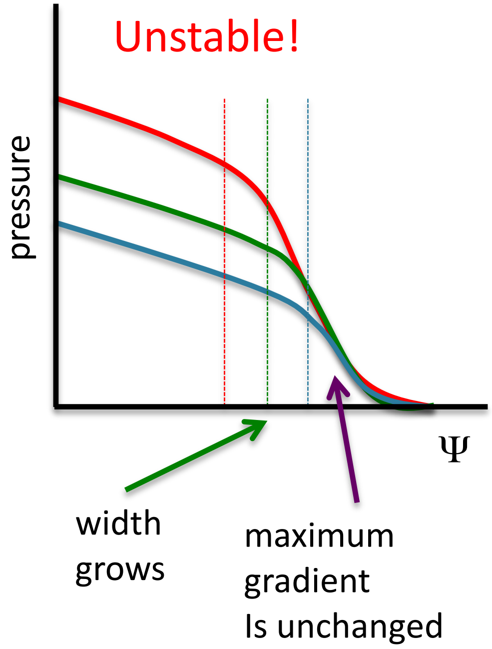

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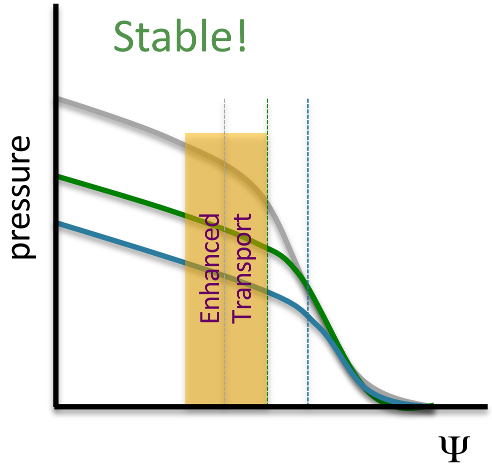
  - Something stops widening of pedestal before threshold
  - Requires enhanced transport at $\Psi \approx 96\text{–}97\%$



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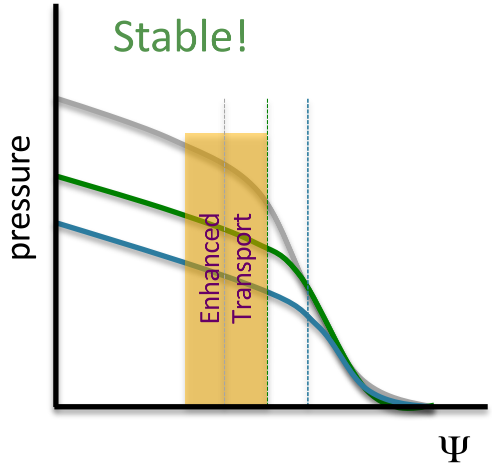

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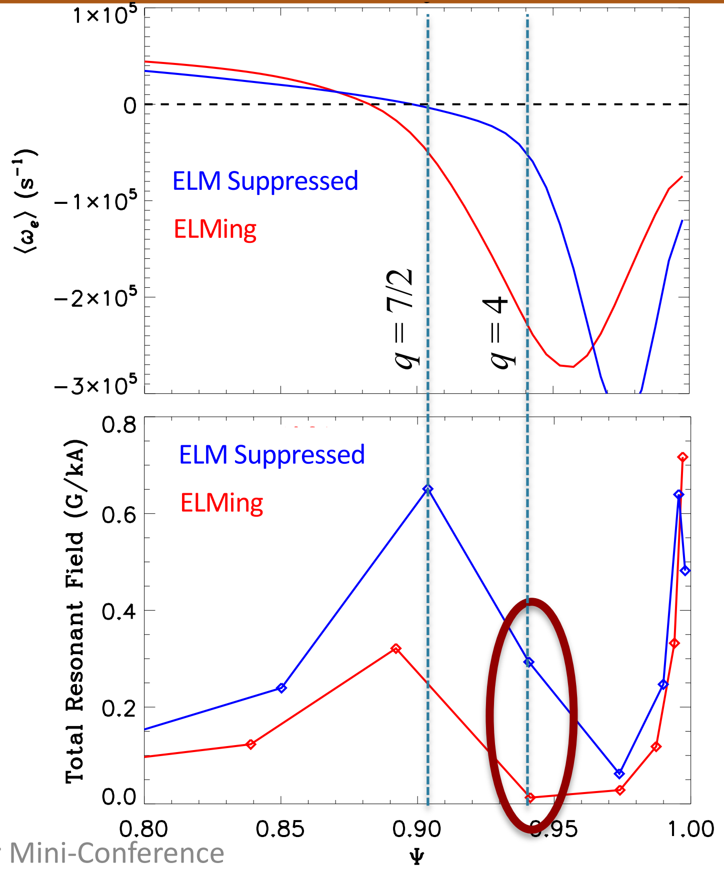
- Predictive modeling needs model of RMP effect on transport
  - Enhanced neoclassical transport?
  - Turbulent transport (KBM)?
  - Magnetic islands / stochasticity → parallel transport?

Significant Enhancement of Tearing Response Calculated in ELM-Suppressed State

- Measurements show change of rotation and pressure profiles in ELM-suppressed state
  - *c.f.* Nazikian, *et al. PRL* **114**, 105002 (2015)

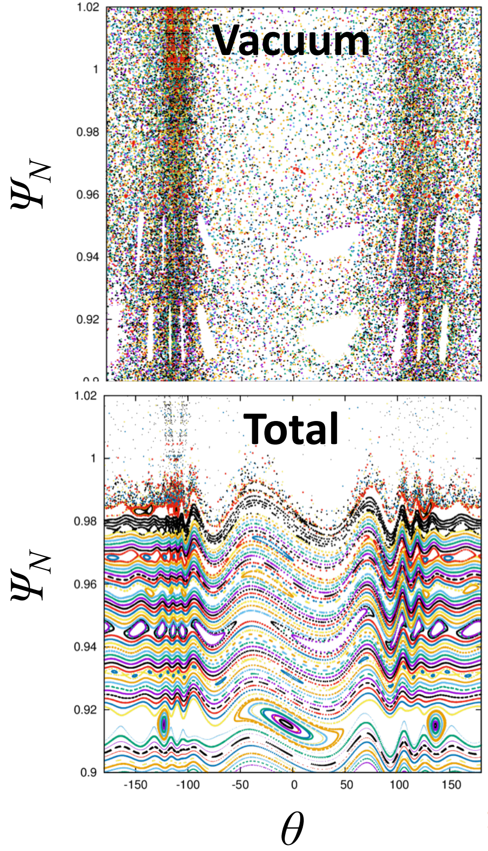
- Modeling shows enhanced tearing near pedestal top in ELM-suppressed state
  - $\omega_e = 0$ moves outward
  - M3D-C1 shows enhanced tearing response where ω_e is small

- Still, implied islands would be small; is this enough to stop pedestal growth?
  - Need to quantify this!



New Project Will Combine 3D Tokamak Equilibrium & Transport Calculations to Understand ELM Suppression

- 3D equilibria can be calculated with M3D-C1
  - Plasma response strongly affects magnetic geometry
  - Allows islands, stochasticity
  - Two-fluid effects are important in edge due to strong diamagnetic flows
- Effect on various types of transport can then be calculated
  - Interfaces have already been developed between M3D-C1 and XGC, GTC, SPIRAL, TRIP3D, EMC3-EIRENE, and 3D NEO
- Goal is to analyze broad set of data
  - Lots of noise introduced by individual EFIT reconstructions; need statistics
  - DIII-D, NSTX(-U), MAST(-U), KSTAR, AUG(?), EAST(?)



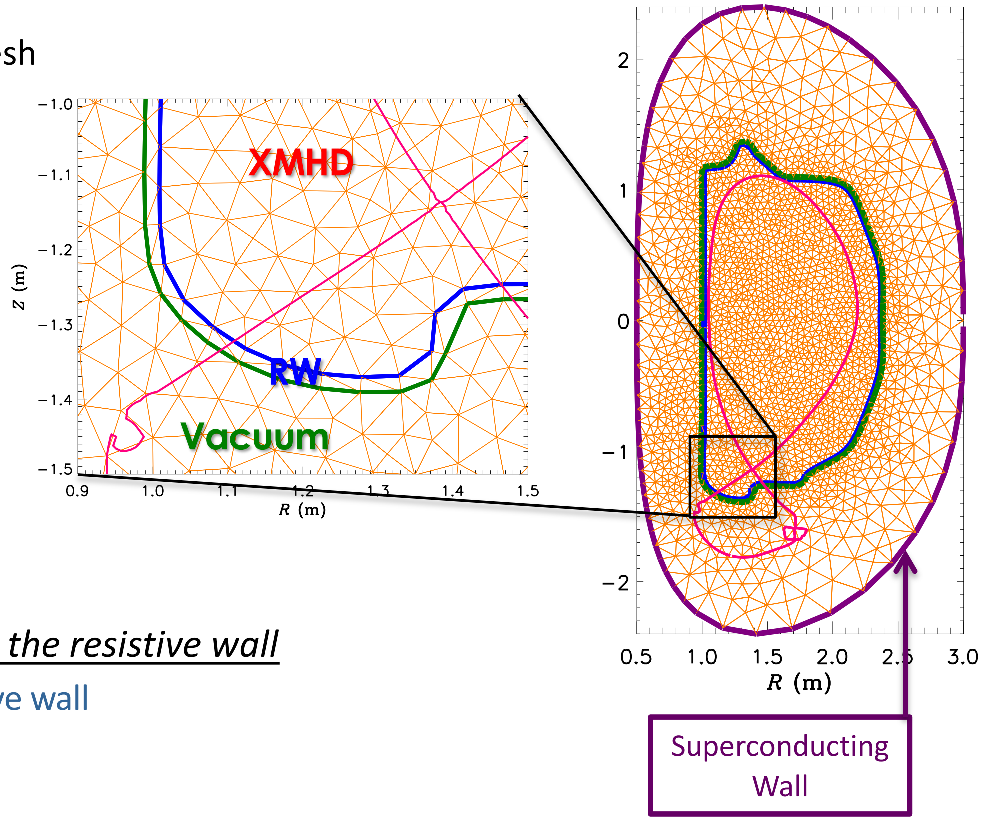
Summary

- ITER is counting on RMP ELM suppression – but we don't know under what conditions it will work
- Pedestal models suggest ELM suppression might be due to enhanced transport at top of pedestal
- New project is underway to evaluate various transport channels given high-fidelity 3D tokamak equilibrium calculations
  - Lots of crosscutting issues with stellarators here!
- Ultimately, we seek a validated, predictive model of RMP ELM suppression to gain confidence that it will work in reactor-relevant scenarios

Extra Slides

M3D-C1 Is Parallel, Finite-Element Code Using Unstructured, Multi-Region Mesh

- Triangular C1 finite elements on unstructured mesh
- 3 regions inside domain:
  - XMHD (Extended MHD)
  - RW ($\mathbf{E} = \eta_W \mathbf{J}$)
  - Vacuum ($\mathbf{J} = 0$)
- Boundary conditions:
  - $\mathbf{v}$, p, n set at inner wall
  - $\mathbf{B}$ set at outer (superconducting) wall
- <u>*There are no boundary conditions on* B *or* J *at the resistive wall*</u>
  - Current can flow into and through the resistive wall



Two-Fluid Extended MHD Model

$$\frac{\partial n}{\partial t} + \nabla \cdot (n_i \mathbf{v}) = 0$$

$$n_i m_i \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi_i$$

$$\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p + \Gamma p \nabla \cdot \mathbf{v} = -\frac{1}{n_e e} \mathbf{J} \cdot \left(\Gamma p_e \frac{\nabla n_e}{n_e} - \nabla p_e \right) - (\Gamma - 1) \nabla \cdot \mathbf{q}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta \mathbf{J} + \frac{1}{n_e e} (\mathbf{J} \times \mathbf{B} - \nabla p_e)$$

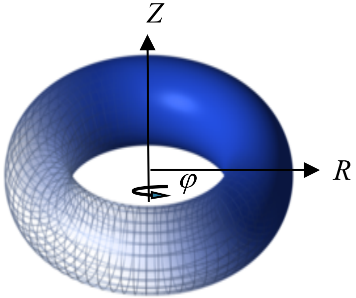
$$\Pi_i = -\mu \left[\nabla \mathbf{v} + (\nabla \mathbf{v})^T \right] + \Pi_i^{gv} + \Pi_i^{\parallel}$$

$$\mathbf{q} = -\kappa \nabla T_i - \kappa_{\parallel} \mathbf{b}\mathbf{b} \cdot \nabla T_e$$

$$\mathbf{J} = \nabla \times \mathbf{B}$$

$$\Gamma = 5/3$$

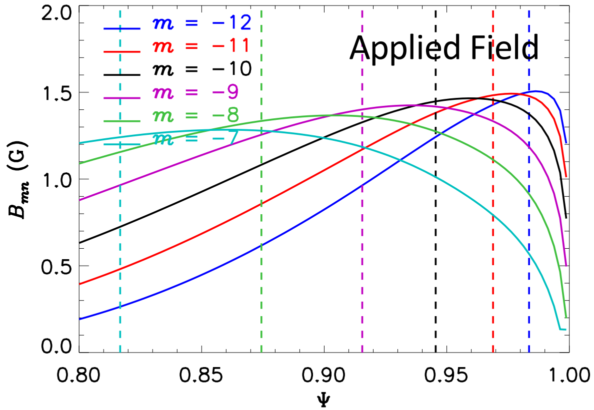
$$n_e = Z_i n_i$$

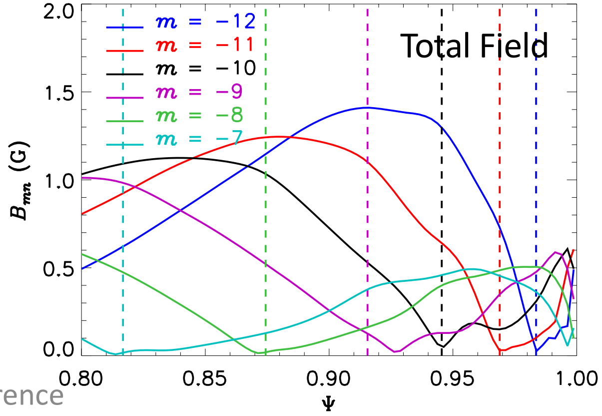


- (R, φ, Z) coordinates → no coordinate singularities in plasma
- Boundary conditions:
  - Linear, time-independent (**plasma response**) – single n
  - Linear, time-dependent (**linear stability**) – single n
  - Nonlinear, time-dependent (**nonlinear evolution**) – toroidal finite elements

Linear MHD Modeling Shows "Kinking," "Screening," and "Tearing" in Response

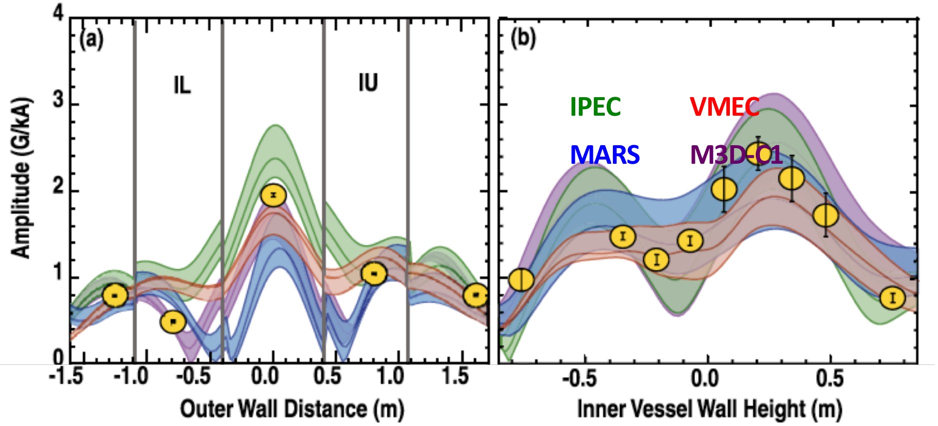
- **Kinking**: amplification of <u>non-resonant</u> field components
  - Makes distortion of surfaces larger than implied by applied fields
- **Screening**: reduction of <u>resonant</u> field components
  - Makes islands smaller than implied by applied fields
- **Tearing**: when plasma response fails to screen <u>resonant</u> components
  - Only possible in non-ideal response



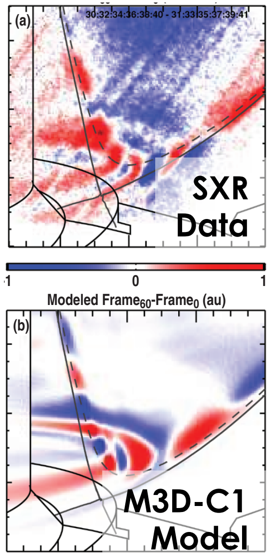


Experiments Clearly See "Kink" Response

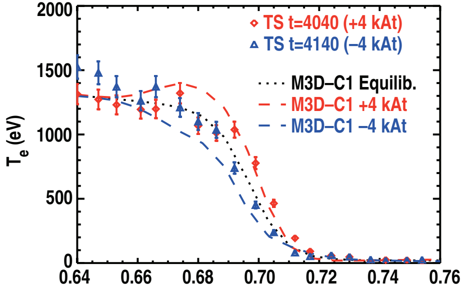
- Including plasma response is necessary to accurately model edge measurements
  - T_e, n_e profiles in edge strongly affected by "kink" response
  - Linear modeling is successful in reproducing measured profiles; magnetics data



JD King, *et al.* *Phys. Plasmas* **22**, 072501 (2015)

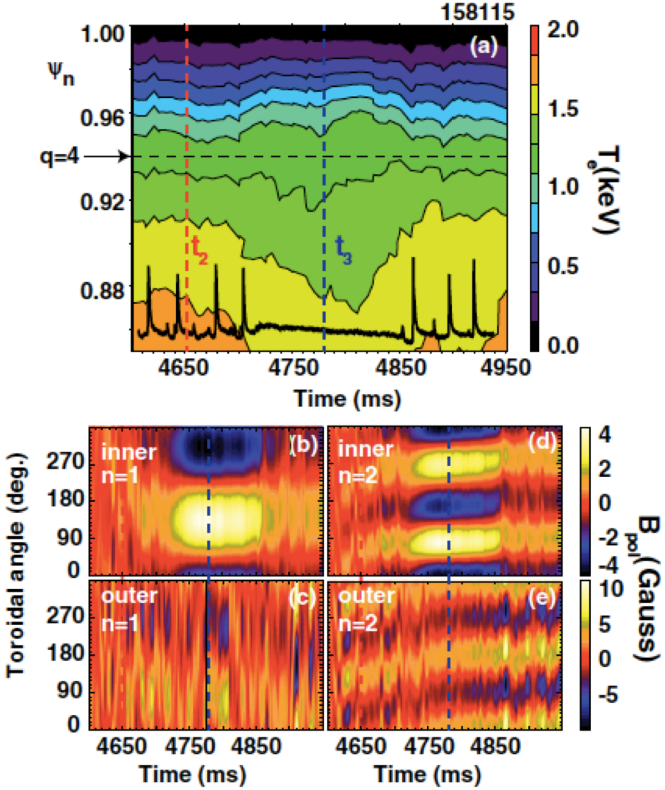


NM Ferraro, *et al.* *Nucl. Fusion* **53**, 073042 (2013)



Experiments See Hints of Island Formation

- Measuring small islands (~1 cm) is very difficult experimentally
- In transition into ELM-suppressed state, a bifurcation similar to the formation of a locked island is observed
  - Temperature flattening near top of pedestal
  - Non-rotating magnetic signal
- No island is seen directly. Modeling is still needed to understand results
  - Truly predicting island formation requires nonlinear modeling



Nazikian, *et al.* *PRL* **114**, 105002 (2015)